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Recent advances in high current vacuum arc ion sources for heavy ion fusion

Niansheng Qi[a], Jochen Schein[a], Rahul R. Prasad[a,*], Mahadevan Krishnan[a], Andre Anders[b], Joe Kwan[b], Ian Brown[b]

[a] *Alameda Applied Sciences Corporation, Suite 230, 2235 Polvorosa Avenue, San Leandro, CA 94577, USA*
[b] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Abstract

For a heavy ion fusion induction linac driver, a source of heavy ions with charge states 1+–3+, ≈0.5 A current beams, ≈20 μs pulse widths and ~10 Hz repetition rates is required. Thermionic sources have been the workhorse for the Heavy Ion Fusion (HIF) program to date, but suffer from heating problems for large areas and contamination. They are limited to low (contact) ionization potential elements and offer relatively low ion fluxes with a charge state limited to 1+. Gas injection sources suffer from partial ionization and deleterious neutral gas effects.

The above shortcomings of the thermionic ion sources can be overcome by a vacuum arc ion source. The vacuum arc ion source is a good candidate for HIF applications. It is capable of providing ions of various elements and different charge states in short and long pulse bursts and high beam current density.

Under a Phase-I STTR from DOE, the feasibility of the vacuum arc ion source for the HIF applications was investigated. We have modified an existing vacuum arc ion source at LBNL to produce a gadolinium ($A \approx 158$) ion beam with >0.5 A beam current, 120 keV beam energy, ≈6 cm diameter extraction aperture and ≈20 μs pulse width. The average beam current density at the extraction grids was ≈17 mA/cm^2. We have measured that >85% Gd ions were in the 3+ charge state, the beam current fluctuation level (rms) was ≈3%, pulse-to-pulse variation of the beam (rms) was about 3%, the uniformity of the beam density over its 6 cm diameter was ⩾98% and the ion longitudinal energy spread was ⩽1%. Additional measurements were made to improve charge state purity by using other materials and employing an axial magnetic field close to the cathode. Yttrium ($A \approx 89$), lead ($A \approx 207$), and Ba ($A \approx 137$) were tested at similar current parameters with Ba delivering nearly a pure charge state with >95% being in 2+ state. The results of the experiments indicate that the vacuum arc ion source is a good candidate for HIF applications.

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Keywords: Heavy ions; Vacuum arc; Ion source; Plasma initiation

1. Introduction

An induction linear accelerator that produces energetic (5–10 GeV) beams of heavy ions (atomic mass = 100–238) is a prime candidate for application in a power-producing inertial fusion reactor.

*Corresponding author. Tel.: +1-510-483-4156; fax: +1-510-483-8107.
E-mail address: prasad@aasc.net (R.R. Prasad).

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The basic idea is to inject one or multiple long beam bunches, several meters in length and $\approx 20\,\mu s$ in duration, and to arrange for the inductive accelerating fields to compress the pulse to $\leqslant 10\,ns$ with ion energy of 5–10 GeV [1,2]. To make $\sim 1\,GW$ electricity production, it requires a high brightness beam with a repetition rate of $\sim 10\,Hz$. Therefore, a practical Heavy Ion Fusion (HIF) reactor requires a reliable heavy ion source operating at 1–10 Hz rep-rates and producing ions mostly in a single charge state.

Thermionic sources have been the workhorse for the HIF program to date, but suffer from slow turn-on, heating problems for large areas are limited to low (contact) ionization potential elements and offer relatively low ion fluxes with a charge state limited to $Q = 1+$. Gas injection sources suffer from partial ionization and deleterious neutral gas effects. The vacuum arc ion source [3–5] (See also the accompanying papers in this issue by authors from many different laboratories around the world) is therefore a potential candidate source for heavy ion fusion. Extracted ion beam currents $> 10\,A$ have been produced (Ti and Ta, for example), and ion current densities of $\sim 100\,mA/cm^2$ can be obtained. The beam ions are predominantly in charge states between $1+$ and $3+$ depending on the metal species used. Higher charge state ions shorten the required length of the accelerator, reducing the number of magnet cores and quadrupoles needed. A biased grid can be used in the arc region to electrostatically separate ions from electrons, preventing plasma pre-fill in the extraction gap and allowing rapid and quiescent beam formation [4].

Based on our earlier studies of a $\approx 0.12\,A$ vacuum arc ion source [6], a high current ($\approx 0.5\,A$) vacuum ion source was investigated for the HIF application. Gadolinium ($A \approx 158$) ion beams with $> 0.5\,A$ beam current, 120 keV beam energy, $\approx 6\,cm$ diameter extraction aperture and $\approx 20\,\mu s$ pulse width were produced. The beam current density at the extraction grids was $\approx 17\,mA/cm^2$. We have measured that $> 85\%$ Gd ions were in the $3+$ charge state, the beam current fluctuation level (rms) was $\approx 3\%$, pulse-to-pulse variation of the beam (rms) was about 3%, the uniformity of the beam density over its 6 cm diameter was $\geqslant 98\%$ and the ion longitudinal energy spread was $\leqslant 1\%$. Additional measurements were made to improve charge state purity by using other materials and employing an axial magnetic field close to the cathode. Gadolinium ($A = 158$), yttrium ($A \approx 89$), lead ($A \approx 207$) and barium ($A \approx 137$) were tested at similar current parameters with barium delivering a nearly pure $2+$ charge state with $> 95\%$ purity. An external magnetic field was applied to increase the percentage of higher charge states. The experimental results indicate that the vacuum arc ion source is a promising candidate for HIF applications. The rest of this paper is arranged as follows: Section 2 describes the experimental apparatus. Section 3 presents the results of the experiments and Section 4 discusses their implications.

2. Description of the experimental apparatus

Fig. 1 shows a schematic drawing of the vacuum arc ion source. The source consists of a vacuum arc plasma generator (cathode/anode/trigger combination, forming the plasma gun) and a set of three ion beam formation electrodes (commonly called the extractor grids). Metal plasma formed at the cathode plumes through the annular anode towards the extractor grids, where ion separation

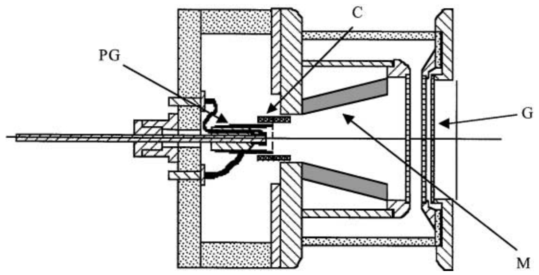

Fig. 1. Drawing of the vacuum arc ion source. The source consists of an arc plasma generator (PG) (cathode/anode/trigger pin combination, forming the plasma gun) and a set of the extractor grids (G). Plasma formed at the cathode plumes through the annular anode towards the extractor grids, where ion separation and acceleration occurs. A coil C produces an electric field to influence plasma parameters and bucket magnets (M) were used to control the expansion of the plasma.

and acceleration occurs. A magnetic multicusp was used to control the expansion of the plasma. Also, a small ($\sim 100\,\mathrm{G}$) magnetic field, produced by a coil surrounding the arc region, was added occasionally to help stabilize the plasma plume in the forward direction. A high current beam of metal ions was produced and exited through the grounded final extractor grid. The cathode was 6.25 mm in diameter and the anode was a 25-mm diameter Al tube. A fine W wire mesh was stretched over the annular anode to stabilize the arc discharge. The anode–cathode gap was 15 mm. The extractor grids were made of 0.5-mm thick stainless steel with 31 beamlet holes, each 6-mm in diameter. The total effective beam extraction area was about $2.2\,\mathrm{cm}^2$. The spacing between the metal grids (extraction gap) was $\approx 7.5\,\mathrm{mm}$. Provided the source is optimized geometrically and electrically for a specific design performance, the ion beam current is determined by the arc current level, which is in turn controlled by the arc power supply voltage and the geometry of the extraction grids. The beam energy is determined by the extraction voltage. The arc power supply circuit determines beam pulse length and repetition rate.

A major improvement was made to this source in comparison to conventional arc sources by using self-triggered initiation of the arc. This method makes a separate high voltage trigger obsolete thereby simplifying the electric circuit and stabilizing the arc initiation. Such self-triggered operation of a vacuum arc was first described by Anders et al. [7]. To ignite the arc, the insulator around the cathode was coated with a thin graphite, conducting layer, which was then connected using a $10\,\Omega$ resistor to the anode. The graphite coating may lead to plasma contamination and was used in these experiments because of the convenience of application. However, contamination issues can be overcome by applying a thin film of the same material as the cathode. When the relatively low voltage arc pulse power was switched with a solid state switch (SCR), a current through this conducting layer was produced. The power density locally was sufficiently high for plasma production and arc initiation. The arc plasma was then transferred to the anode directly across the vacuum gap. The advantages of this approach are a less erratic trigger and cleaner plasma production.

A low-impedance 10-stage LC pulse-forming network supplied the arc current. The output of the PFN pulser has a $\approx 20\,\mu\mathrm{s}$ flattop with a $1\,\Omega$ impedance, which is much higher than the $\sim 40\,\mathrm{m}\Omega$ of the arc plasma. The PFN was charged to a voltage of 1–1.2 kV delivering an arc current of up to 600 A. A three grid accel-decel system was used for beam extraction. The typical value of net acceleration voltage was $\approx 40\,\mathrm{kV}$.

A magnetically suppressed Faraday cup with a 9-mm diameter entrance aperture located 200-mm downstream of the extraction grids was inserted into the beam path to measure the beam current. This Faraday cup could be moved over a diameter of 60 mm, allowing a full scan of the ion beam. The charge state distribution of ions was measured using a time-of-flight (TOF) diagnostic. The beam passes through an annular electrostatic beam deflector, the throughput of which can be electrically gated on for a time period of approximately $0.2\,\mu\mathrm{s}$. The transmitted burst of ions, accelerated through the same extractor potential, subsequently drifts down a region of sufficient length to enable different charge-to-mass components to spatially separate. The ions are collected downstream at the end of the axial drift region with a Faraday cup as a current monitor. The current contains a predictable time sequence of pulses representing the arrival of ion bunches with a descending order of charge state. The charge state distribution is determined by the relative pulse heights, taking into account the variable contribution of each particle to the measured current due to its charge state.

3. Experimental results

The experiments reported here concentrated on the ion beam profile, beam current noise, shot-to-shot variation and ion charge state composition. Most beam current, profile and stability measurements were made with a gadolinium ($Z = 64$) cathode. To search for a material with adequate mass and promise to produce plasma with a very dominant charge state, gadolinium ($Z = 64$), yttrium (39), lead (82), and barium (56) were tested.

3.1. Gd ion beam profile

The beam profile was determined using the scanning Faraday-cup. Fig. 2 presents the measurement of the ion current with respect to the radial position of the Faraday-cup done for a 600 A gadolinium arc, with an extraction voltage of 40 kV. It can be seen that up to 35 mm away from the center of the ion beam, the beam current remains nearly constant, with a large drop towards the fringes. A very homogeneous beam profile with variations of less than 2% over a diameter of 60 mm was produced. This result can be improved further if an additional magnetic field is used. However, for HIF it is critical that there is no residual field in the ion beam extraction region as this field adversely affects the emittance growth of the beam.

Integrating the current densities over the area delivers the overall beam current, which is shown in Fig. 3. The total Gd ion beam current was ≈ 0.63 A with small ripple (± 0.01 A). For a quiescent beam pulse, a primary requirement is that the associated power supplies themselves have adequately low ripple or fluctuation level. To achieve $<1\%$ current variation, as required for HIF application, the ripple of the acceleration voltage must be $<0.7\%$, which is not difficult to achieve.

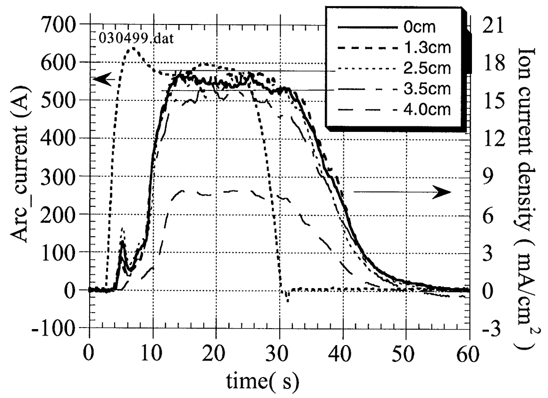

Fig. 2. Radial scan of the ion beam current using a Faraday-cup with a 0.9-cm diameter aperture. The numbers in the graph show the distance of the Faraday cup center to the beam center.

3.2. Beam stability

The Gd arc and beam current amplitude stability (the noise) of the beam was found to be less than 3% rms. The beam current rise time was found to be $\approx 3\,\mu$s. The small foot in the ion beam current stems from the contamination (mostly H and C ions) that is produced during ignition.

Additional experiments were performed with an applied magnetic field (<100 G), which was produced by a coil surrounding the plasma gun. It turned out that an additional 50% reduction of the beam noise, amplitude fluctuation, respectively, were achieved. Unfortunately, the application of a magnetic field tends to obstruct the anode attachment; possibly leading to the so-called anode spots, in which metal plasma of the anode material is produced. This enhances contamination of the ion beam. The fine mesh covering the annular anode is thought to alleviate the issue of anode spot formation.

3.3. Beam charge state composition

Time-of-flight measurements have been made to determine the ion charge states. The ion charge state spectrum is important for HIF applications and can, to a large extent, be selected by choosing the appropriate cathode material.

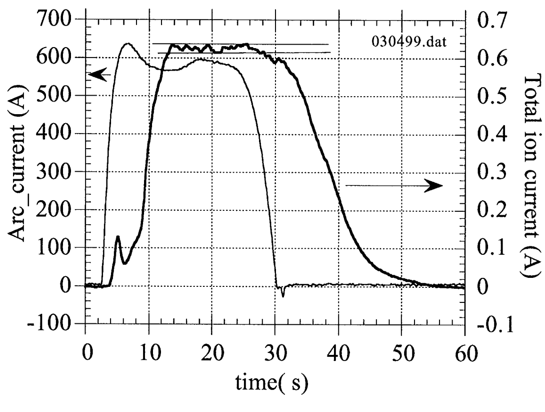

Fig. 3. Total ion beam current for 600 A arc current and 40 kV extraction voltage.

Fig. 4 shows a typical spectrum of the 120 keV Gd ion beam. A gate pulse of $\approx 1\,\mu s$ was used. Comparing the shape of the signal to the shape of the original gate pulse allowed an evaluation of the energy spread of each charge state. The charge state distribution is peaked at 3+ with small components at 2+ and 4+. Unfortunately, the spectrum is not very clean showing contamination components of hydrogen and carbon. These can be avoided by using a conductive layer (to use the self-triggered initiation) of the cathode material rather than the graphite that we used. The charge state has been found to be >85% 3+ with a longitudinal energy spread <1% at 120 keV, i.e. <1.2 keV. For HIF, this energy spread is below the 2 keV requirement for a 2 MeV beam.

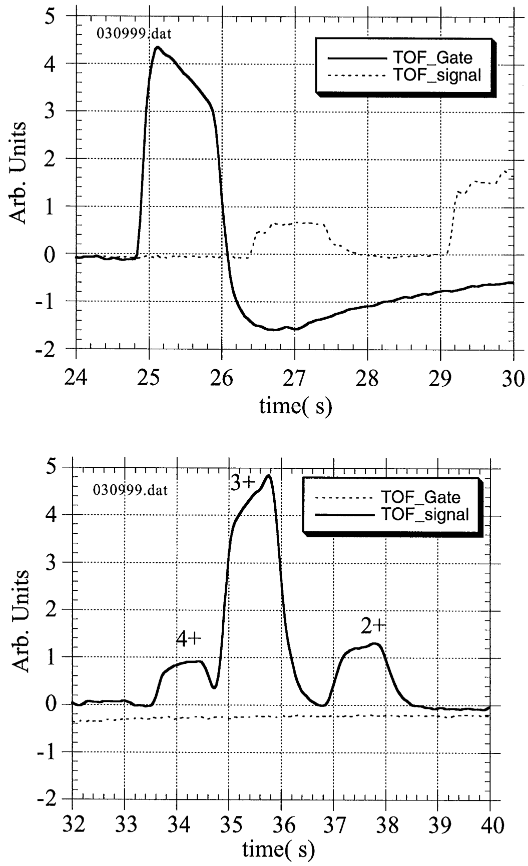

Fig. 4. TOF pulse and Gd signal for 600 A and 40 kV extraction voltage. The upper figure shows the detail of the TOF pulse. The lower figure shows the detail of the Gd signal, which is delayed with respect to the TOF pulse. The charge state was found to be >85% 3+ with a longitudinal energy spread <1% at 120 keV, i.e. <1.2 keV. For HIF, this energy spread is below the 2 keV requirement for a 2 MeV beam.

Purity of the charge states is also extremely important for Heavy Ion Fusion. In order to achieve this goal measurements with materials other than Gd have been made. The basic idea is to make use of the electron shell structure of the elements. If a large potential gap exists, ionization might be stopped at the ion charge state, which is just under this potential barrier. Taking into account availability, the materials that were chosen were yttrium, lead and barium.

Yttrium has a relatively low potential of ionization for the doubly charged ions but a high potential for the triply charged ions. Its charge state distribution (CSD) was measured to be 5% in +1, 62% +2, and 33% +3. The CSD spectrum of Pb has been measured: 36% +1 and 64% +2. A very encouraging result was achieved with barium: >95% of 2+ charge states were measured as shown in Fig. 5. The small spread in CSD in barium is due to a very low ionization potential of the neutral atom and singly charged ions, $E_0 = 5.54$ eV and $E_1 = 10.00$ eV, respectively, combined with a relatively high ionization potential of the doubly charged ions, $E_2 = 34.45$ eV.

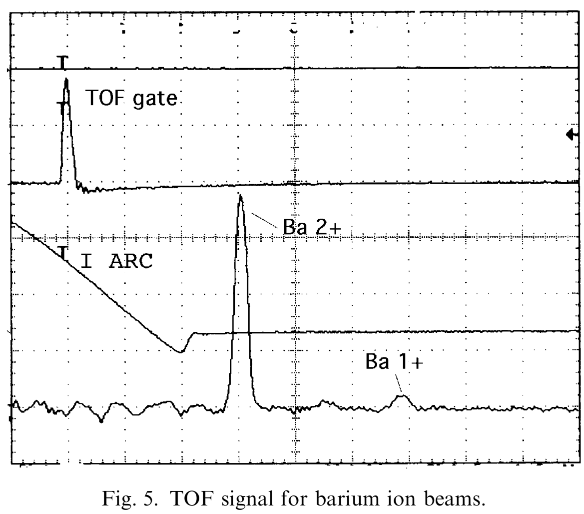

Fig. 5. TOF signal for barium ion beams.

4. Discussion and conclusion

In the experiments reported here, we have demonstrated that a high current, flat current profile, low current fluctuation level, and high ionization charge state, heavy ion beam can be produced from a vacuum arc ion source. A $\approx 6\,\text{cm}$ diameter uniform gadolinium ion beam was accelerated to 120 keV with a beam current of $\approx 0.6\,\text{A}$. It corresponds to a current density of $21\,\text{mA/cm}^2$. The ion current density is not limited by the plasma flux near the acceleration grids. Increasing the beam current density to $\approx 100\,\text{mA/cm}^2$ can be achieved by using properly designed and fabricated beam acceleration grids to operate at higher acceleration field. The rms beam current fluctuation level was 3%. Low noise levels like this are not typical for vacuum arcs and are highly dependent on the cathode material condition. Small amounts of contamination can reduce noise levels but unfortunately the reproducibility of these special material conditions is difficult to achieve. About 85% Gd ions were in the 3+ charge state with <1% energy spread. Further improvements of the beam profile, noise, stability and charge state distribution may be possible. In the past, we have measured an emittance of $\approx 0.3\pi$ mm mrad (normalized) at $\approx 0.12\,\text{A}$ level [6]. Possibilities to achieve the same or better emittance at higher ion beam current levels will be examined in future. The parameters achieved in the experiment imply that vacuum ion sources have interesting properties that make them attractive for HIF applications.

Acknowledgements

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